Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 14 (2011) 1071–1078

Procedia Engineering

www.elsevier.com/locate/procedia

The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction

Traffic-Induced Response Prediction of Highway Bridges

D. SU[a], J. LAOMENIT, and Y. FUJINO

Department of Civil Engineering, University of Tokyo, Japan

Abstract

Composite steel I girder bridge is a very common structural type in Japanese highway network. Understanding such bridges' behavior thoroughly is important for design implementation as well as maintenance aspect. In this research, dynamic stress response of a steel girder bridge inducing by a passing vehicle is investigated analytically as well as by field measurement. The object bridge consists of three identical spans, which adopts steel I-girders seated on the elastomeric bearings. A field measurement was performed on the bridge to monitor dynamic response passing by a 25-ton truck. Then a numerical vibration prediction model of traffic-induced response is established. After the proposed model is verified through the comparison between the calculated results and the in situ measured data, it is extended to study the influence of elastomeric bearing on the dynamic responses. It was found that the natural frequencies of the bridge and the global stress response are in good agreement. However, the discrepancies between the local responses reveal great influence from the unknown elastomeric bearing stiffness for the static stress component and the dynamic stress component. Furthermore, the analysis shows the influence from the bearing stiffness is very different for the various part of the bridge.

Keywords: Finite Element Model, Vehicle-Bridge dynamic interaction, Monitoring, Road roughness, Bearing stiffness.

1. Introduction

The problem of bridge vibrations induced by moving vehicles has been a topic of interest for more than half a century. For Japanese highway network, traffic has increased greatly in the past few years and a great number of bridges that have been used for ages might deteriorate due to environment or increasing traffic volume. Therefore, evaluation of bridge performances are needed to determine whether they should be rehabilitated reconstructed or remained in operational condition. In order to correctly assess the

[a] Corresponding author and presenter: su@bridge.t.u-tokyo.ac.jp

1877–7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2011.07.135

performance of highway bridges, it is essential to be able to predict their structural responses to in-service loads. A precise numerical model that incorporates dynamic effects is required, because passing vehicles generally produce significantly greater responses than static vehicular loads. One of the main difficulties is that the real boundary conditions of the bridge cannot be obtained by simple experiment, especially for the bridge using elastomeric bearings. In this research, the target bridges are composite steel I-girder bridges which are supported by rubber bearings. This type of bearing has been widely used after Kobe earthquake in order to reduce the transmission force from substructure to superstructure. The influence of this bearing type to the bridge response caused by traffic vibration has been studied among researchers in many areas. Kawatani et.al (2000) has examined influence of elastomeric bearing to the acceleration response and dynamic reaction force of the bridge. He also made a comparison between responses from steel bearing which act as the pin support and elastomeric bearing. It was concluded that acceleration response upon the bearing from the bridge with rubber bearing caused larger vibration than that with steel bearing. In other word, the impact vibration on the vehicle at the expansion joint (above the bearing) became larger due to the rubber bearing. For dynamic reaction force, both steel bearing and elastomeric bearing absorbed the similar dynamic reaction force in the transverse and vertical direction whereas in the longitudinal direction (bridge axis) dynamic reaction force became small in the case of rubber bearing.

In this study, the vehicle-bridge decoupled equations of motion are implemented with the commercial FE method software ABAQUS and the general numerical software MATLAB. This analytical procedure is applied to a full-scale steel I-girder bridge that has been monitored. After the proposed model is verified through the comparison between the calculated results and the in situ measured data, it is extended to study the influence of elastomeric bearing on the dynamic responses. Finally, the suggestions to bridge maintenance learned from the simulation are discussed.

2. Traffic-induced vibration in highway bridge

2.1. Bridge descriptions and field measurement

In this study three simply supported spans were chosen to measure the dynamic response characteristics excited by both a 25-ton passing truck and free traffic flow. The tested bridge was built in 1962, which are part of the Tokyo Metropolitan expressway in Japan (Figure 1). It carries four-lane traffic, which has two lanes on each bound. In each span, it is a simply supported, single-span, composite bridge. The 210 mm reinforced concrete slab is supported by five main steel I-girders at a spacing of 3.5 m. The bridge is 31.9 m long and 16.5 m wide. All main girders are seated on elastomeric bearings.

The configuration of loading path and strain gauge locations are illustrated in Figure 2. During day time (free traffic flow), the acceleration recorded with a sampling frequency of 250 Hz were computed by applying the Eigensystem Realization Algorithm (Juang and Pappa 1985) to obtain the bridge natural frequencies which are about 3.1-3.2 Hz and 3.5-3.7 Hz for the first bending and the first torsion mode, respectively. During night time, a 25-ton truck running on each lane, i.e. lane No. 1 to lane No. 4 with a speed of 50 km/h, 60km/hr and 70km/hr is KL-FW1KXHA of Hino's company. 19 strain gauges recoding at every 0.01 second were installed mainly on the top surface of the bottom flanges, except gauge No.2, No7 and No. 18, No.19. They were placed on the web plates of the exterior girders and top surface of the top flange of the transverse steel girder about 400 mm from the center of the main interior girder, respectively.

Figure 1: Monitored bridge.

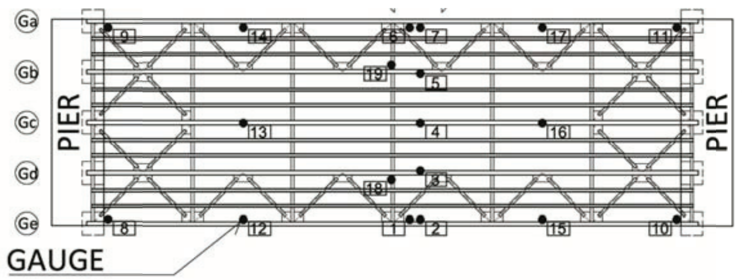


Figure 2: Plan view of one span and sensor positions.

2.2. Vehicle-bridge interaction system

A versatile numerical procedure is developed in order to simulate the dynamic interaction between the bridge and the vehicle, incorporating the effect of road surface roughness. The method is implemented with standard commercial software and is therefore easily applicable to various types of bridges. The detailed algorithm will not be introduced here, which can be seen in Reference (Fujino 2009). Overall schematic flow of the methodology is illustrated as a diagram in Figure 3.

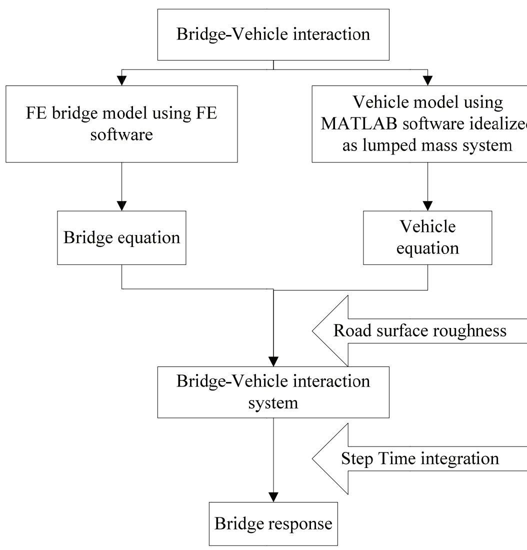


Figure 3: Schematic flow of the methodology.

2.3. The bridge model

The bridge was modeled based on its as-built drawing by using ABAQUS. All structural elements were modeled as solid elements. For boundary conditions, the bridge is seated on an elastomeric bearing. Linear spring was selected to represent the bearing's characteristic. The stiffness constant of spring was calculated from the Japanese design code (Japanese Road Association 2004). The material models for both the steel and concrete were linearly elastic, with Young's moduli equal to 206,000 and 28,000 MPa, Poisson ratios equal to 0.3 and 0.2, respectively. For the Rayleigh damping ratio, 1% and 5% were chosen for both material models. The parameters of the elastomeric bearing coefficients were chosen as 0.8 GPa, 2.5 MN/m and 700 MN/m for shear modulus, transverse stiffness and vertical stiffness, respectively.

2.4. The vehicle model

The controlled 25-ton four-axle truck passed on the bridge in order to record the interaction controlled response. It was idealized as a rigid body for the upper part and a series of linear springs and dampers for the suspension system. The 11 degrees of freedoms was selected to represent the vehicle system illustrated in Figure 4. Some of the vehicle parameters are obtained from calibration test and some are from the literature (Fukada et al. 2007). The vehicle model can be verified by checking the natural frequencies of the vehicle which are usually about 3 Hz for the air suspension system and the tire system are about 10-20 Hz in Japan (Fukada et al. 2007).

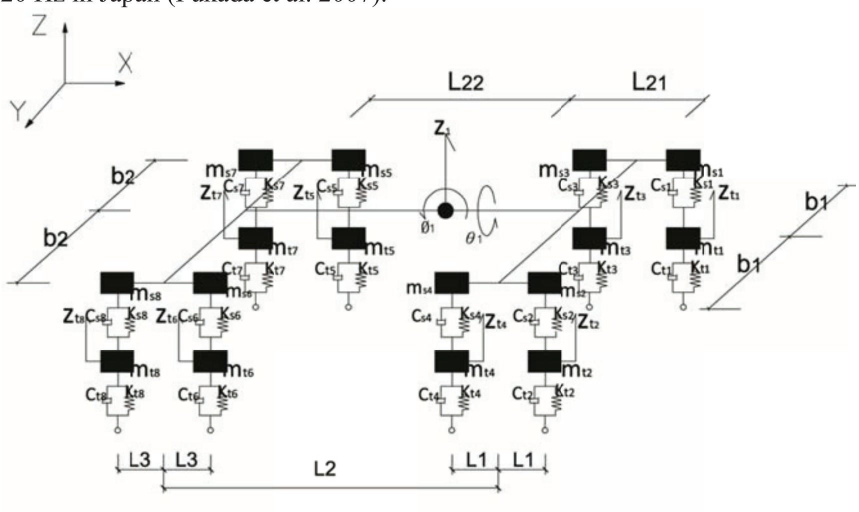
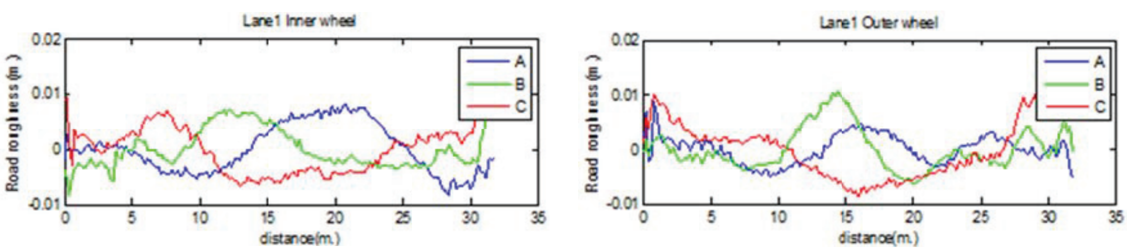


Figure 4: The vehicle model.

2.5. Road surface roughness

The road surface roughness can be obtained either by measuring the road with a special inspection car. In this study, the road surface roughness of the pavement measured by a special inspection car used for simulation was assumed to be at the same path as the moving vehicle path as illustrated in Figure 2. One example of each span when moving on lane 1 is shown as Figure 5.



Inner wheel

Outer wheel

Figure 5: Road surface roughness of lane 1 of three spans

3. Numerical simulation

The bridge finite element model was verified by the field measurement. The model validation consists of two steps: the first step was to check the bridge modal properties with comparison of bridge frequencies analyzed from acceleration during free-traffic flow and vehicle model properties as described previously; the second step was to adjust the bridge properties for predicting local dynamic response such as the stress near the bearing by comparison with the dynamic response obtained during a moving vehicle test on the bridge. Finally, the comparisons of the dynamic stress component between the measurement and the simulation results are described.

3.1. Model adjustment and verification

To check the bridge properties and the vehicle properties, the frequency analysis of the bridge model and vehicle model are processed. The natural frequencies of the bridge model based on design drawing are 2.8 and 3.3 Hz for the first bending and the first torsion mode, respectively which are about 5-10% lower from the measured ones.

3.2. Static and dynamic response

The bridge-vehicle interaction was performed for each load case and speed. The stress responses will be compared in two frequency ranges which are the low frequency stress response at a cutoff frequency of 0.85 Hz defined as static stress component and band pass frequency of 1-5 Hz classified as dynamic stress component as shown in Figure 6.

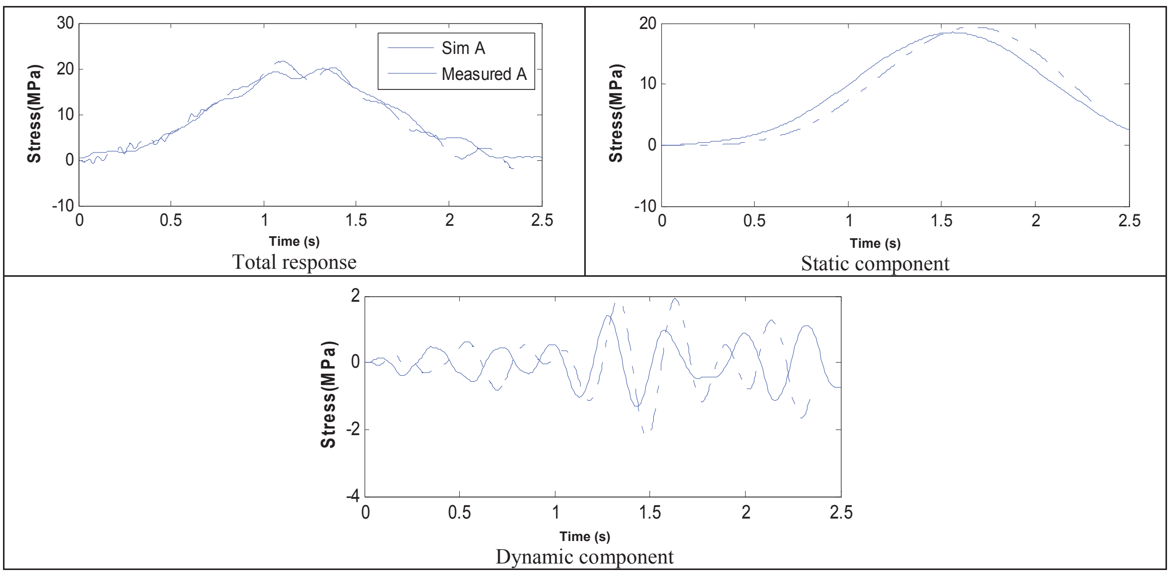


Figure 6: Simulated and measured stress results (gauge No.6).

From the comparison, they are comparable for almost all the positions under the moving path. However, clear discrepancy still could be seen in Figure 6. The unknown elastomeric bearing stiffness and the inaccurate road roughness input could be the causes, which will be analyzed in the following sections.

3.3. Influence of boundary conditions on natural frequencies

The previous researches revealed that the bearing stiffness in the later section that the discrepancies observed in the measurement are influenced by the transverse bearing stiffness. The bearing model shown in Figure 7 consists of two transverse directions (K_H), one vertical direction (K_V) and two rotational directions (K_r). The parameters α, β and γ in Table 1 as illustrated in Figure 7 are the stiffness ratio in each direction used in the model to the designed value computed based on the Japanese design code. For the frequency analysis as provided in Table 1, the frequencies of the bending and torsional mode increased as the transverse stiffness constant increased. However, it is found that the influence of the bearing stiffness on the frequencies is quite small.

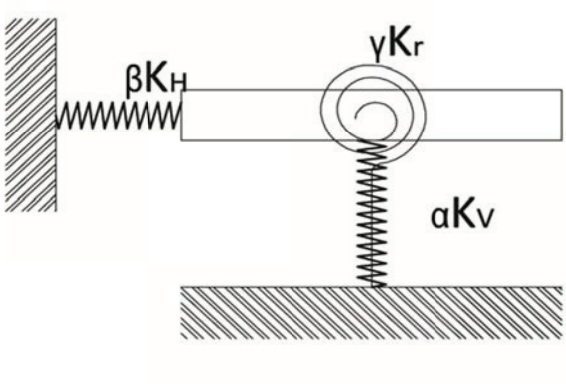


Figure 7: The linear spring model of elastomeric bearing.

Table 1: Bridge frequencies with different bearing stiffness models

Case	Bearing stiffness magnification			1st bending mode (relative difference)	1st torsional-lateral mode (relative difference)
	Vertical (α)	Transverse(β)	Rotational (γ)		
B1	1	1	1	2.78 Hz (10.3%)	3.39 Hz (4.55%)
B2	1	5	1	2.83 Hz (8.7%)	3.42 Hz (3.66%)
B3	1	10	1	2.89 Hz (6.92%)	3.51 Hz (1.04%)
B4	1	15	1	2.94 Hz (5.30%)	3.58 Hz (0.84%)
B5	1	20	1	2.98 Hz (3.84%)	3.55 Hz (0.08%)

For the static stress response, by changing the transverse stiffness ratio, Figure 8 and Figure 9 show the stress response at Gauge No.9 (near the end-bearing) and Gauge No.6 (at the mid span) with different bearing stiffness, respectively. From the comparison, large difference could be seen in the part near the end-bearing, which indicates the stress response in this part is very sensitive to the status of the bearing. Meanwhile the responses in the mid span are almost the same under the different bearing stiffness cases. The influence from the bearing stiffness in different parts of the bridge should be clarified in the bridge design.

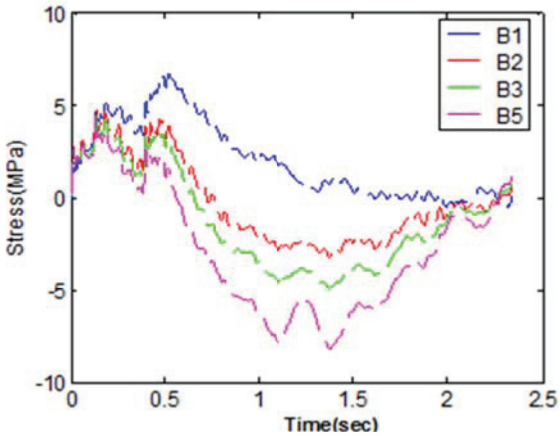


Figure 8: The static stress responses at Gauge No.9 (Truck in lane 1 with 60 km/h).

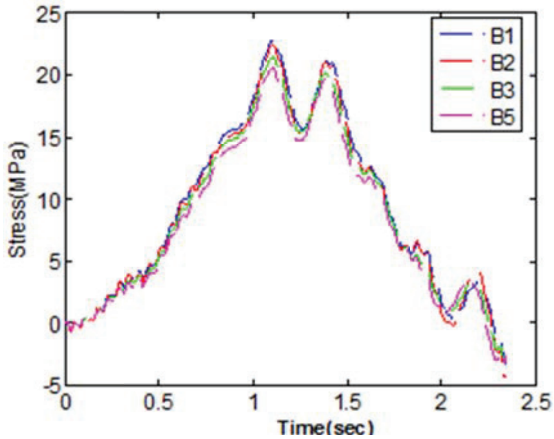


Figure 9: The static stress responses at Gauge No.6 (Truck in lane 1 with 60 km/h)

3.4. Comparison under different stress level

By observing and calculating the normalized of summation of the difference between the measurement and the simulation results η defined in Equation (1), where ε is the dynamic stress component of experiment and simulation and ll is the length of data.

$$\eta = \frac{\sum_{i=1}^{ll.} \left| \varepsilon_{\exp} - \varepsilon_{sim} \right|}{ll} \tag{1}$$

The differences of all gauges are summarized in Figure 10. Among three spans, one can observed that for the lower stress level which the first four gauges corresponding to the gauges no.1, 12, 15, 2, respectively, located far from the moving path show large variations as compared with the locations near the moving path. These are still the limitation of this bridge FE model to predict the dynamic stress response in the low stress level, although they are not really important from the practical view. Since the magnitude of stress is very small, the difference could be neglected. However, the most important location (the critical stress occurred) could predict well with small difference in order of 0.2 MPa. It proves that the model can accurately predict both local and global dynamic stress responses in the structure.

4. Conclusion

From the simulation results of the identified three-span bridge provided the following conclusions. The bridge FE model could predict the bridge frequencies as well as the static stress component. From the parametric studies on the bearing stiffness, the transverse stiffness of the bearing affects significantly on the static stress responses located near the bearing whereas it causes small influence on static responses at mid-span and other locations. Secondly, for the dynamic stress component observed from the simulation results at the gauges located far from the moving path, they are still

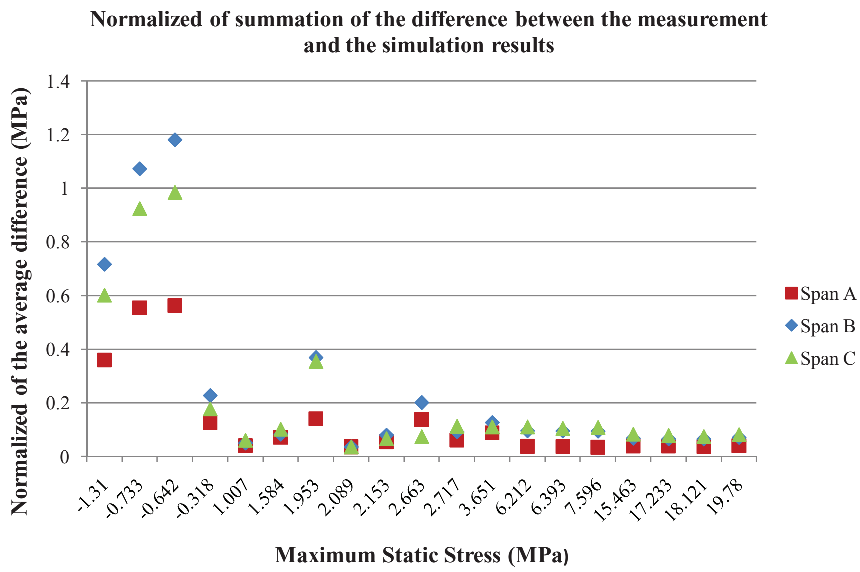


Figure 10: Normalized of summation of the (Truck in lane 1 with 60 km/h).

predicable compared with the measurement. Finally, the model is proved that it can accurately predict both local and global dynamic stress responses in the structure.

Acknowledgments

The second author wishes to express her deep appreciation to the Japanese Ministry of Education, Culture, Sports, Science and Technology for its financial scholarship support. The authors express immense gratitude to the Technical Center of Tokyo Metropolitan Expressways Public Corporation for their active collaboration throughout all phases of the field measurement.

References

[1] Fukada S. *Dynamic response analysis of a test bridge due to running vehicle*. Proceedings of International Modal Analysis Conference XXV, Jacksonville, Florida USA, No. 046; 2007..

[2] Fujino Y, Su D, Wyss J. *Prediction of traffic-induced vibration characteristics in a skew bridge.* Proceedings of 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure (SHMII-4), Zurich, Switzerland; 2009..

[3] Japan Road Association. *Design specification of the bearing for highway bridges*. Maruzen. (in Japanese); 2004.

[4] Juabg J and Pappa R. *An eigensystem realization algorithm for modal parameter identification and model reduction*. Journal of Guidance, Control and Dynamics, 8; 1985, pp. 620-627.

[5] Kawatani M, Kobayashi Y, Kawaki H. *Influence of elastomeric bearings on traffic-induced vibration of highway bridges*. Transportation research record: Journal of the transportation research board, No.1696, TRB, National research council, Washington D.C., 2000, pp. 76-82.